Quantized electron transport by interference-induced quantum dots of two cross-travelling surface acoustic waves

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In traditional approaches of obtaining quantized acoustoelectric current, a narrow channel is fabricated to form quantum dots, which hold a fixed number of electrons at a certain depth. We propose a natural way of forming quantum dots without the narrow channel, by the interference of two surface acoustic waves (SAWs) propagating across each other. A wide transportation area is defined by the usual (but widely separated) split-gate structure with another independent gate in between. This design can increase the quantized current by one to two orders of magnitude. The three-gate structure also allows separate control of the barrier height and the side-gate pinch-off voltage, thus avoids current leakage through the area beneath the side gates.

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Surface acoustic wave (SAW) travelling in a piezoelectric substrate produces an accompanying wave of electrostatic potential. When interacting with a two dimensional electron gas (2DEG), the wave can drag electrons and drive a current. If a narrow channel is put along the SAW direction, it combines with the moving potential trough to make a quantum dot, which at a certain depth carries a fixed number of electrons due to Coulomb blockade. Devoices based on the above idea have produced quantized acoustoelectric current $I = nef$ (where n is the number of electrons in each dot, f is the SAW frequency) with f in the gigahertz band [1, 2]. Such quantized acoustoelectric current can potentially serve as a current standard in the nanoamps range [3]. To increase the current further, Ebbecke *et al* invented a double-channel structure to duplicate the current [4]. In this Letter, we propose a natural way of realizing multiple (up to 10 or 100) transportation lines in a single 2DEG, without fabricating physical channels.

The idea is to make use of the interference pattern of two waves. As depicted in Fig. 1, two SAWs of the same frequency and perpendicular directions are launched along the surface of a piezoelectric substrate such as GaAs/AlGaAs heterostructure. The surface is in the (100) plane of the GaAs cubic crystal. The two SAWs are travelling in the two perpendicular and symmetric directions [011] and [0$\bar{1}$1], respectively. A 2DEG resides some tens of nanometers below the surface. In the interfering region of the two SAWs, arrays of potential peaks and wells are formed (see Fig. 2). At sufficiently high SAW power, the bottoms of the wells can be regarded as quantum dots. The travelling direction of the quantum dots is along the middle line of the angle made by the wave vectors of the two SAWs. In our case, it is the [001] direction along the x axis. The electron transportation channel is defined by the usual split-gate structure, but with the two gates widely separated so that a row of many quantum dots can pass together. Namely, it is now a multi-line channel. To control the electron number in each dot, a potential barrier must be build into the channel as in previous approaches. However, simply applying a voltage to the two side gates would not work well, because the channel is now wide. In order for the quantum dots to climb over the same potential barrier, a third (middle) gate is added into the channel, with its ends very close to the two side gates. The potential shape of this configuration is roughly illustrated in Fig. 3 [5].

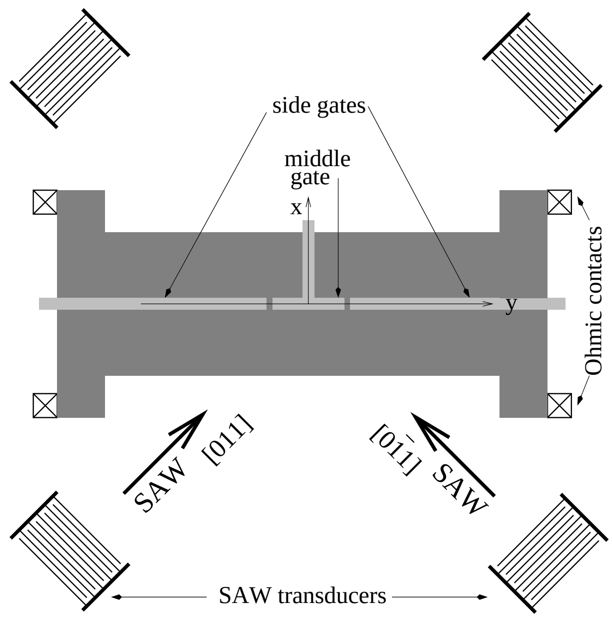

FIG. 1: Schematic diagram of driving acoustoelectric current by two interfering SAWs. A coordinate system is set up as displayed, with the x axis in the [001] direction, the y axis in the [010] direction, and the z axis pointing into the medium. The two SAWs are travelling in the [011] and [0$\bar{1}$1] directions, respectively.

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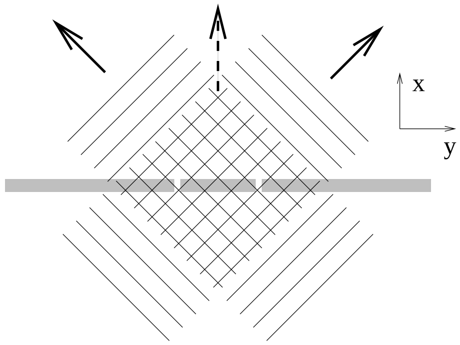

FIG. 2: The interference region. Shaded squares represent the gates. Parallel lines represent the bottoms of the SAW troughs. The cross points are the interference- induced quantum dots. Solid and dashed arrows indicate the travelling directions of the SAWs and quantum dots, respectively.

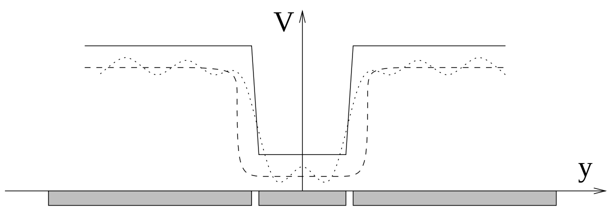

FIG. 3: A rough illustration of the potential shape in the y-z plane. Shaded areas indicate where the gates locate. Solid line is the bare potential (without SAW) at the surface; dashed and dotted lines are potential at the 2DEG without and with the SAW, respectively.

If η is the average number of transportation lines, the quantized acoustoelectric current would be $\eta \times nef$. Since $\eta \sim D/\sqrt{2}\lambda$ (where D is the channel width, and λ is the SAW wavelength) can be made quite large, such a device can potentially deliver a quantized current in the sub-microamps range. The limitation of this approach is essentially set by the Coulomb interaction between the electrons in different dots, which may raise the electron energy too high that the dots can bound no electrons.

The design we proposed brings two extra advantages: First, before encountering the gate barrier, the quantum dots have travelled quite some distance, thus have enough time to capture electrons and to arrange them into stable bound states. Second, the three-gate structure allows separate control of the pinch-off voltage for the side area and the barrier height in the transportation region, thus avoids current leakage through the area beneath the side gates when the barrier height is decreased. We encourage experimental investigation of the interaction of two interfering SAWs with the 2DEG, especially in connection with the theoretical [6, 7, 8, 9, 10, 11] and experimental [12, 13, 14, 15, 16] efforts towards a thorough understanding of the quantization phenomenon of acoustoelectric current.

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